Arc Flash Analysis

Electrical Arc Hazards

- Electrical Arcs can occur when a conductive object gets too close to a high-amp current source (energized conductor).
- Arc Flash Burns
  - The arc can heat the air to temperatures as high as 35,000 F, and vaporize metal.
  - Arc flash can cause severe skin burns by direct heat exposure and by igniting clothing.

Electrical Arc Hazards

- Arc Blast Impacts
  - The heating of the air and vaporization of metal creates a pressure wave that can damage hearing and cause memory loss (from concussion) and other injuries. Flying metal parts are also a hazard.
- Falls
  - Electric shocks and arc blasts can cause falls, especially from ladders or unguarded scaffolding.

Definitions

- Limited Approach Boundary: A shock protection boundary not to be crossed by unqualified persons unless escorted by qualified personnel.
- Restricted Approach Boundary: A shock protection boundary to be crossed by only qualified persons. Shock protection is required.
- Prohibited Approach Boundary: A shock protection boundary to be crossed by only qualified persons. The use of techniques that may require direct contact with energized equipment.

Definitions

- Flash Protection Boundary: Distance at which the incident energy equals 1.2 Cal/cm^2.
- Incident Energy: The amount of energy impressed on a surface, a certain distance from the source, generated during and electrical arc event.
- Working Distance: The dimension between the possible arc point and the head and body of a worker positioned in place to perform the task.
- Bolted fault current: A short-circuit contact between two conductors at different potentials in which the impedance between the conductors is zero.

Definitions

- Available fault current: The electrical current that can be provided by the serving utility and facility-owned electrical generating devices and large electrical motors considering the amount of impedance in the current path.
- Arcing fault current: A fault current flowing through an electrical arc-plasma, also called arc fault current and arc current.
- Voltage (Nominal): A nominal value assigned to a circuit or system for the purpose of designating its voltage class (I.e. 120/240 V, 480Y/277 V, 600V, etc).

Regulating Authorities

- OSHA 29 CFR 1910.132 (d) requires employers to assess the workplace to determine if hazards are present, or likely to be present and select and have each employee use the types of PPE that will protect them.
- OSHA 29 CFR 1910.333 Requires employees who are exposed to electrical shock hazard to be qualified for the specific task that they are performing and use the appropriate PPE

Regulating Authorities

- OSHA 29 CFR 1910.335 (a)(1)(I): Protective equipment for specific body parts
- OSHA 29 CFR 1910.335 (a)(2)(I): use of Insulated tools when working around energized equipment.
- NEC 110.6: equipment must be marked to warn qualified persons of potential electrical arc-flash hazards.
- NFPA 70E-2000 Part II Chapter 2, paragraph 2-1.3.3 states that arc-flash analysis must be performed in order to determine the level of hazard and appropriate PPE for given tasks.

Protection From Arc Flash Hazards

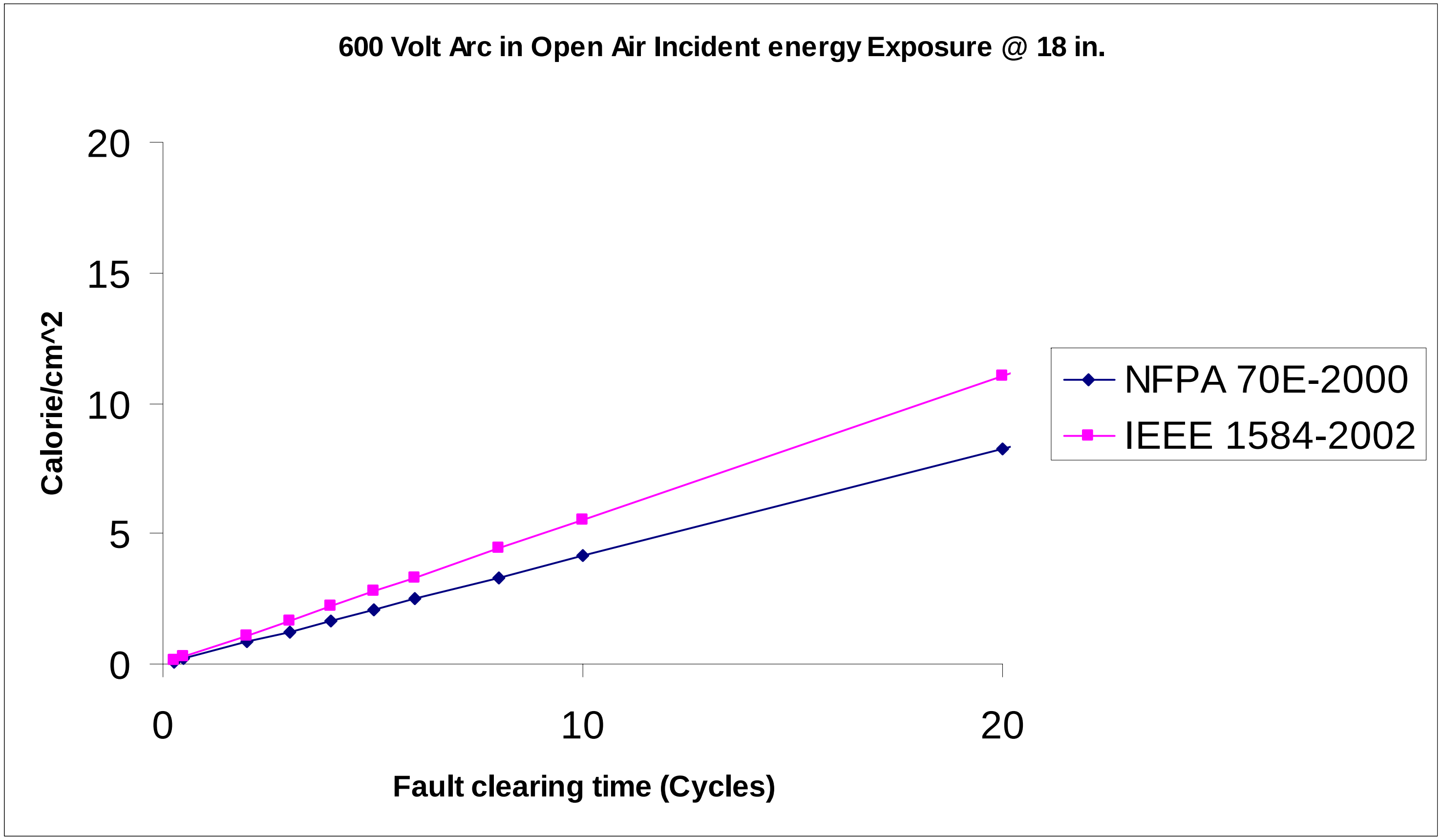
NFPA 70E 2004 “Standard for Electrical Safety Requirements for Employee Workplaces”

IEEE 1584 2002 “Guide for Performing Arc Flash Hazard Calculations”

Comparison of Arc Flash Standards

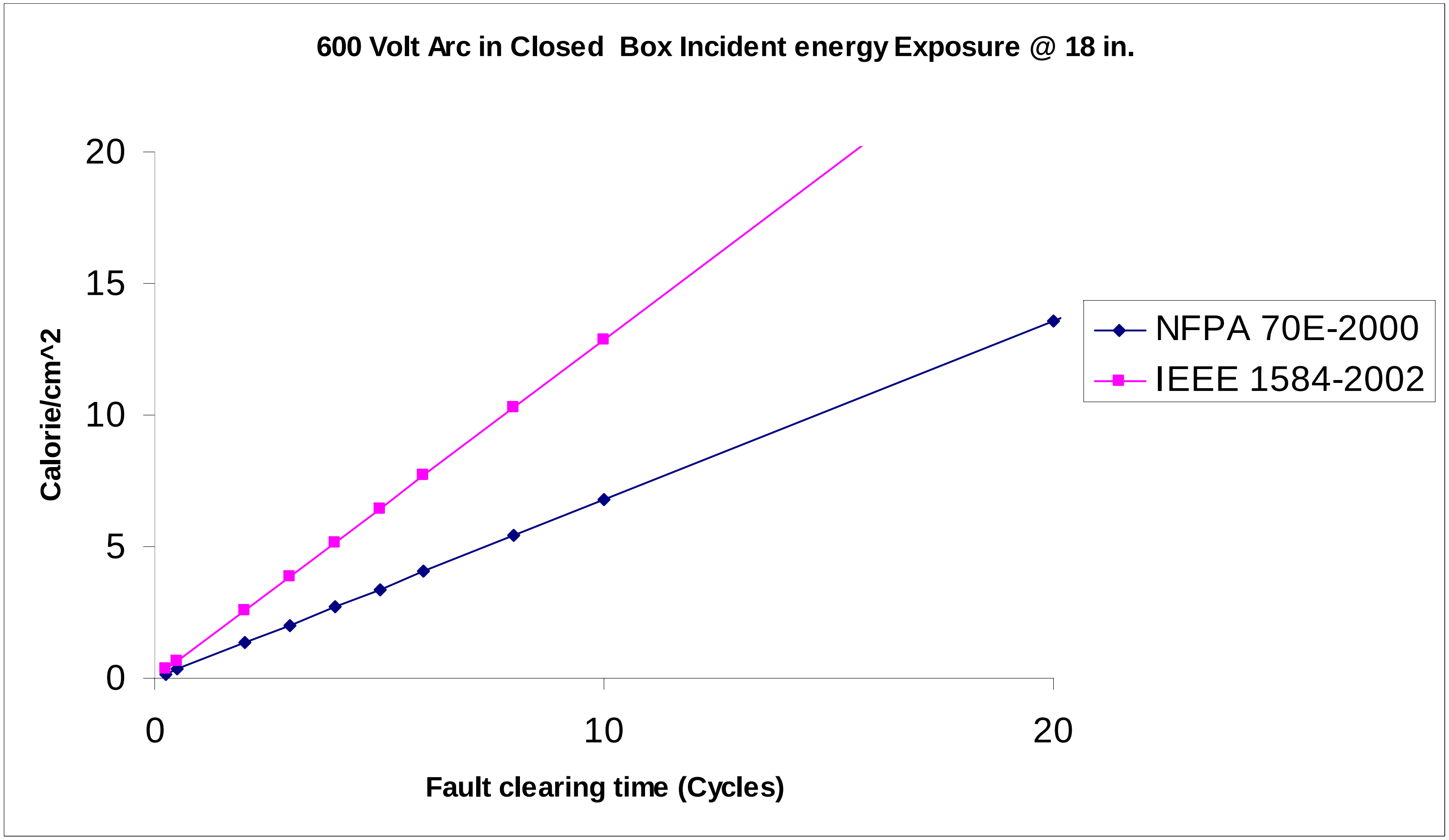
	NFPA 70E-2000	IEEE 1584-2002
Voltage Range	208 V – 600 V	208 – 15 kV (Empirical) 15 kV+ (Lee Method)
Current Range	16 kA – 50 kA	0.7 kA to 106 kA
Arc Duration Range	No limit	No Limit
Installations	Open Air, Cubic Box	Open Air, Cubic Box, Cable Bus
Working Distance	18 inches +	18 inches +
Unit of Measure	Cal/cm^2 or J/cm^2	Cal/cm^2 or J/cm^2

Incident Energy Comparison



Incident energy exposure at a working distance of 18”

for a 19.5 kA Arc @ 600 Volts (open air equipment)



Incident energy exposure at a working distance of 18"

for a 19.5 kA Arc @ 600 Volts (enclosed equipment)

NFPA Hazard Risk Determination Quick Table (Table 3-3.9.1 of 2000 Ed)

- Can you use them exclusively and still be in compliance for Arc-Flash safety?
- Developed based on outdated standard that only covers 600 V systems
- May result in unnecessary overprotection / under protection
- Best when used only in emergency situation for quick evaluation of hazard level
- Standard mandates a detail arc-flash analysis be performed when the task is not specifically covered by this table

General Steps for Performing Arc Flash Analysis

- Collect system information required for the Arc Flash Calculation
- Determine the system operating configuration
- Calculate 3-Phase bolted fault currents
- Calculate arcing fault current (IEEE only)
- Determine arc clearing time (arc duration) -TCC

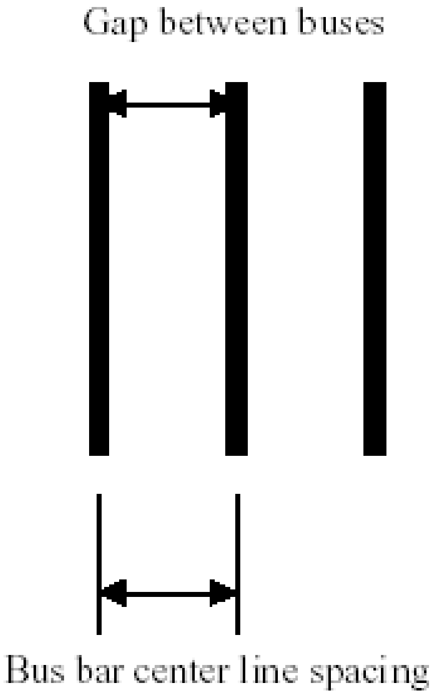
General Steps for Performing Arc Flash Analysis

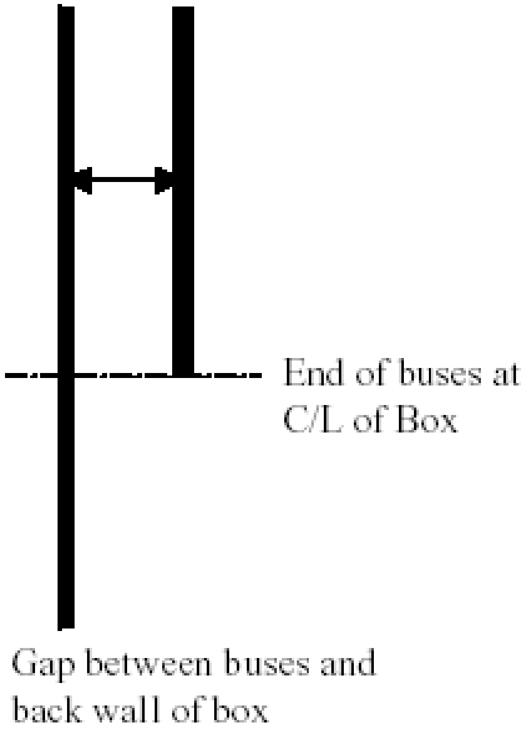
- Calculate Incident Energy
- Determine Flash Protection Boundary
- Determine Hazard/Risk Category based on NFPA 70E requirements
- Select appropriate protective equipment (PPE Matrix)

Data Collection for Arc Flash

Required Parameter	NFPA 70E	IEEE 1584
System Nominal Voltage	X	X
Gap Between Conductors		X
Distance X Factor		X
System Grounding (Grounded/Ungrounded)		X
Open/Enclosed Equipment	X	X
Working Distance	X	X
Coordination Information (TCC)	X	X

Gap between Conductors


Gap between buses
Bus bar center line spacing


End of buses at
C/L of Box
Gap between buses and
back wall of box

Additional Considerations

- Up to date one-line-diagrams
- Data similar to information required for Short-circuit studies like MVAsc values of Utilitiy including X/R, subtransient and transient reactance, cable impedance, etc.
- Include low voltage equipment which is often not included in large systems

3-Phase Bolted Fault Current

- Perform ANSI/IEC short circuit study that considers the following:
  - 3-phase bolted fault
  - ½ cycle or 1½-4 cycle fault current depending on the type of device or system voltage
  - Include all cables & Overload heaters
  - Prefault voltage (nominal circuit voltage)
  - Short-circuit Calculation should be more accurate rather than too conservative (faults may persist longer at lower current levels which may translate into higher energy)

System Modes of Operation

- Open or looped
- One or more utility feeders in service
- Utility interface substation secondary bus tie breaker open or closed
- Unit substation with one or two primary feeders
- Unit substation with two transformers with secondary tie opened or closed
- MCC with one or two feeders, one or both energized.
- Generators running in parallel with the utility supply or in standby mode

Why use 3-Phase Faults

- Line to Line faults quickly escalate into three- phase faults
- LV L-G faults in solidly grounded systems quickly escalate into three phase faults
- LV L-G faults in Ungrounded / High resistance grounded systems do not release enough energy.
- MV faults in low resistance or reactance grounded systems should be cleared quickly, but worst case scenario 3-phase fault should be considered

Standards for Short-Circuit

- IEEE Std 141-1993 (IEEE Red Book)
- IEEE Std 242-2001 (IEEE Buff Book)
- ANSI (different standards like C37, etc)
- IEC (60909, 60363, etc)
- See ETAP help file for more standards

Arcing Current

In general, arcing current in systems below 15.0 kV will be less than the 3-phase fault current because of arc impedance.

For buses with nominal kV in the range of 0.208 to 1.0 kV:

$$\lg(Ia) = K + 0.662 * \lg(I_{bf}) + 0.0966 * V + 0.000526 * G$$
$$+ 0.5588 * V * (\lg(I_{bf})) - 0.00304 * G * (\lg(I_{bf}))$$

Arcing Current

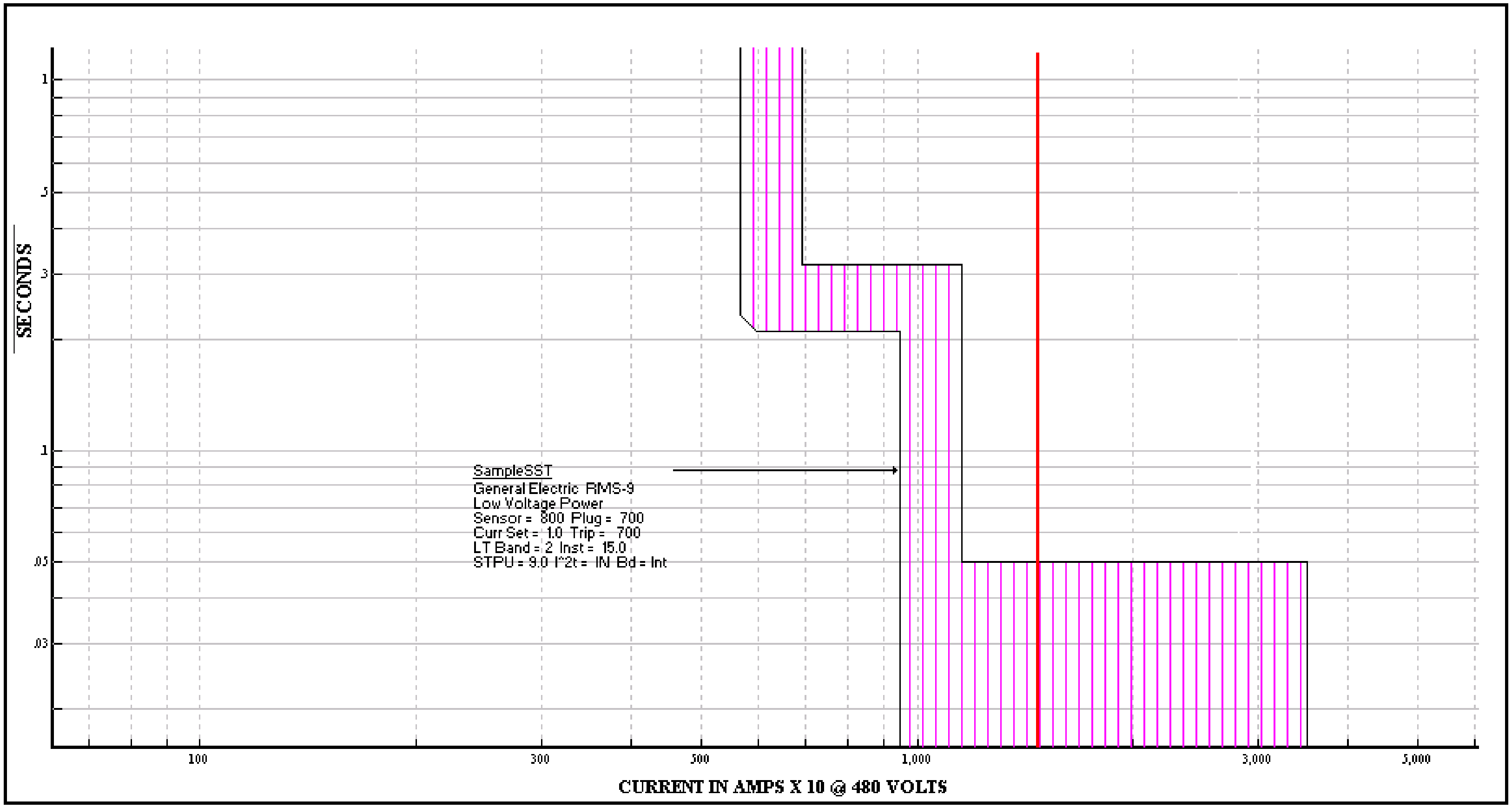
For buses with nominal kV rating in the range of 1 to 15.0 kV:

$$lg(Ia) = 0.00402 + 0.983 * lg(I_{bf})$$

For buses with nominal kV rating greater than 15 kV, the arcing current can be considered to be the same as the bolted fault current:

$$Ia = I_{bf}$$

Arc Duration LV CB



Arc Duration LV CB

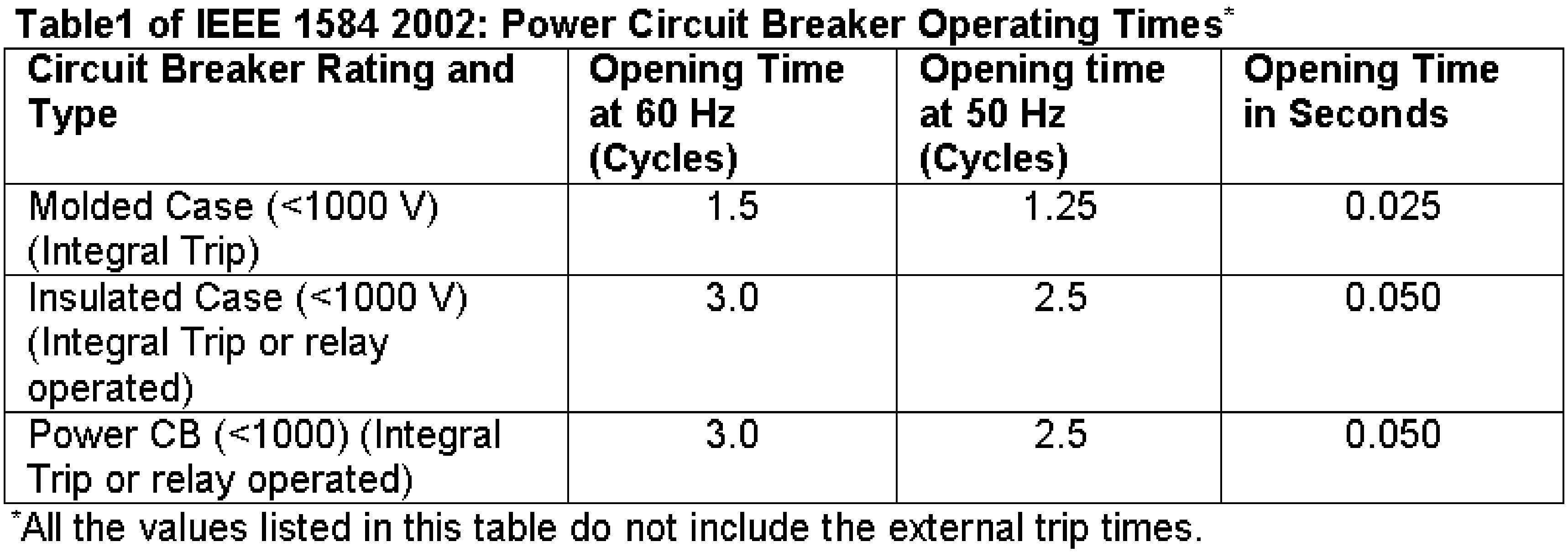
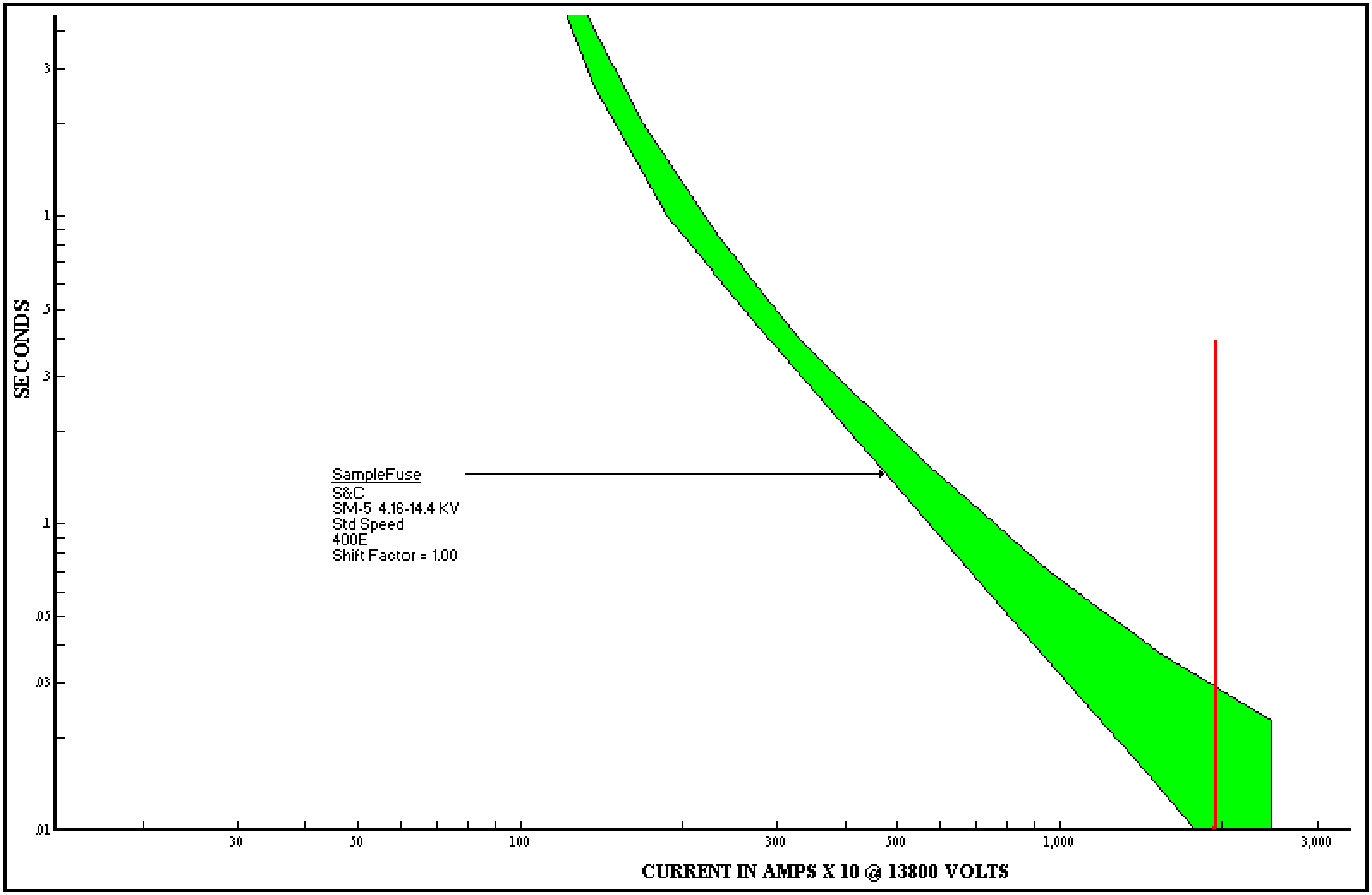


Table1 of IEEE 1584 2002: Power Circuit Breaker Operating Times[*]

Circuit Breaker Rating and Type	Opening Time at 60 Hz (Cycles)	Opening time at 50 Hz (Cycles)	Opening Time in Seconds
Molded Case (<1000 V) (Integral Trip)	1.5	1.25	0.025
Insulated Case (<1000 V) (Integral Trip or relay operated)	3.0	2.5	0.050
Power CB (<1000) (Integral Trip or relay operated)	3.0	2.5	0.050

[*] All the values listed in this table do not include the external trip times.

Arc Duration for Fuses



Incident Energy

Empirical method (1.0 to 15.0 kV)

$$E = 4.184 * C_f * E_n \left(\frac{t}{0.2}\right) * \left(\frac{610^x}{D^x}\right)$$

Lee method (higher than 15.0 kV)

$$E = 2.142 * 10^6 * V * I_{bf} \left(\frac{t}{D^2}\right)$$

Flash Protection Boundary

Empirical method (1.0 to 15.0 kV)

$$1.2 = 4.184 * C_f * E_n \left(\frac{t}{0.2} \right) * \left(\frac{610^x}{D^x} \right)$$

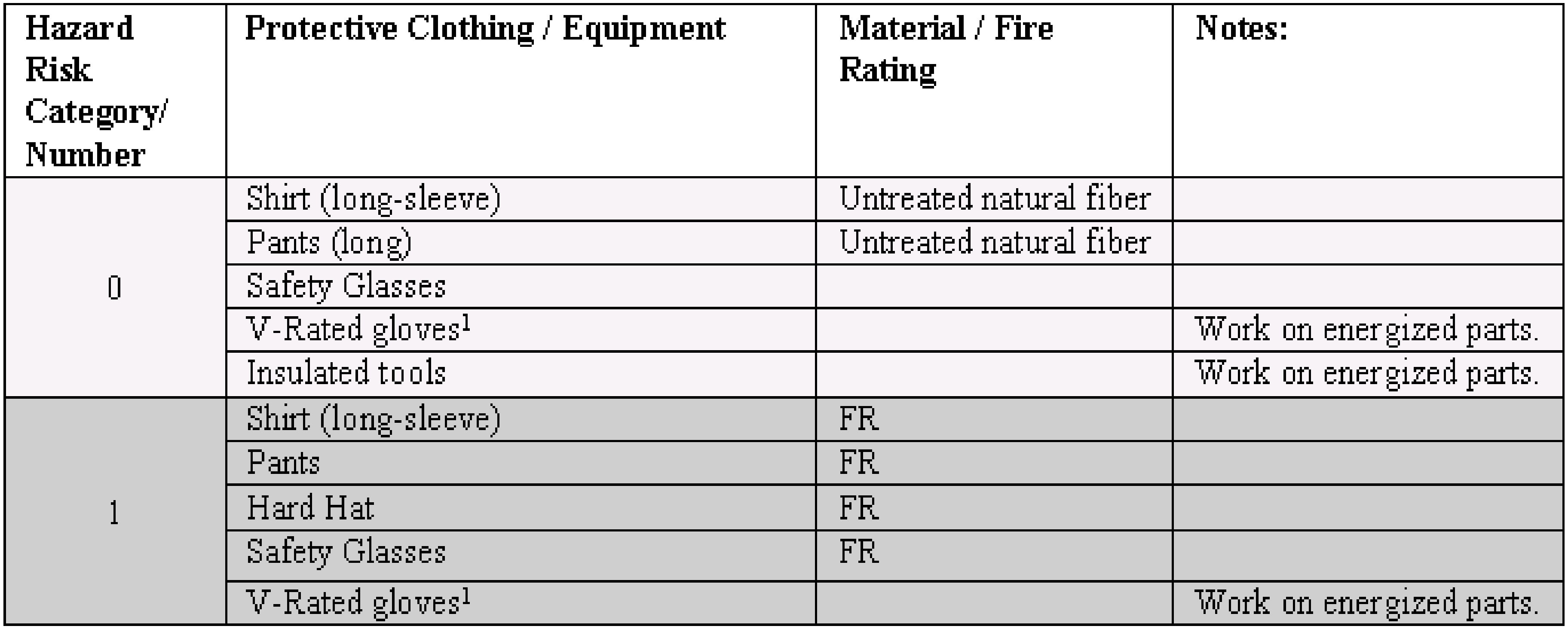
Lee method (higher than 15.0 kV)

$$1.2 = 2.142 * 10^6 * V * I_{bf} \left(\frac{t}{D^2} \right)$$

Hazard / Risk Categories
NFPA 70E 2000

Incident Energy Exposure cal/cm^2	Hazard Risk Category	Total Weight Oz/yd^2
$1.2 > \text{cal/cm}^2 \geq 0$	0	4.5 – 7
$5 > \text{cal/cm}^2 \geq 1.2$	1	4.5 – 8
$8 > \text{cal/cm}^2 \geq 5$	2	9 – 12
$25 > \text{cal/cm}^2 \geq 8$	3	16-20
$\text{cal/cm}^2 \geq 25$	4	24-30

Personal Protective Equipment
PPE Matrix



Hazard Risk Category/ Number	Protective Clothing / Equipment	Material / Fire Rating	Notes:
0	Shirt (long-sleeve)	Untreated natural fiber	
	Pants (long)	Untreated natural fiber	
	Safety Glasses		
	V-Rated gloves[1]		Work on energized parts.
	Insulated tools		Work on energized parts.
1	Shirt (long-sleeve)	FR	
	Pants	FR	
	Hard Hat	FR	
	Safety Glasses	FR	
	V-Rated gloves[1]		Work on energized parts.

Categories 0 and 1 Personal Clothing/Equipment Requirements per Table 3-3.9.2 of NFPA 70E 2000

Category 0 (up to 1.2 Cal/cm^2)

- Shirt (Long-Sleeve)
- Pants (Long)
- Safety Glasses
- V-Rated Gloves
- Insulated Tools

Category 1 (1.2 up to 5.0 Cal/cm^2)

- Shirt (Long-Sleeve) FR
- Pants (Long) FR
- Safety Glasses FR
- V-Rated Gloves
- Insulated Tools
- Hard Hat FR

Category 2 (5.0 up to 8.0 Cal/cm2)

- Category 1 Requirements

plus

- Extra Layer of Untreated Natural fiber (Shirt & Pants)
- Leather Work Shoes

+

FR

FR

Category 3 (8 up to 25 Cal/cm^2)

- Category 2 Requirements

plus

- Coveralls up to 2 Sets
- Double Layer Switching Hood
- Hearing Protection

Category 4 (higher than 25 Cal/cm^2)

- Category 3 Requirements

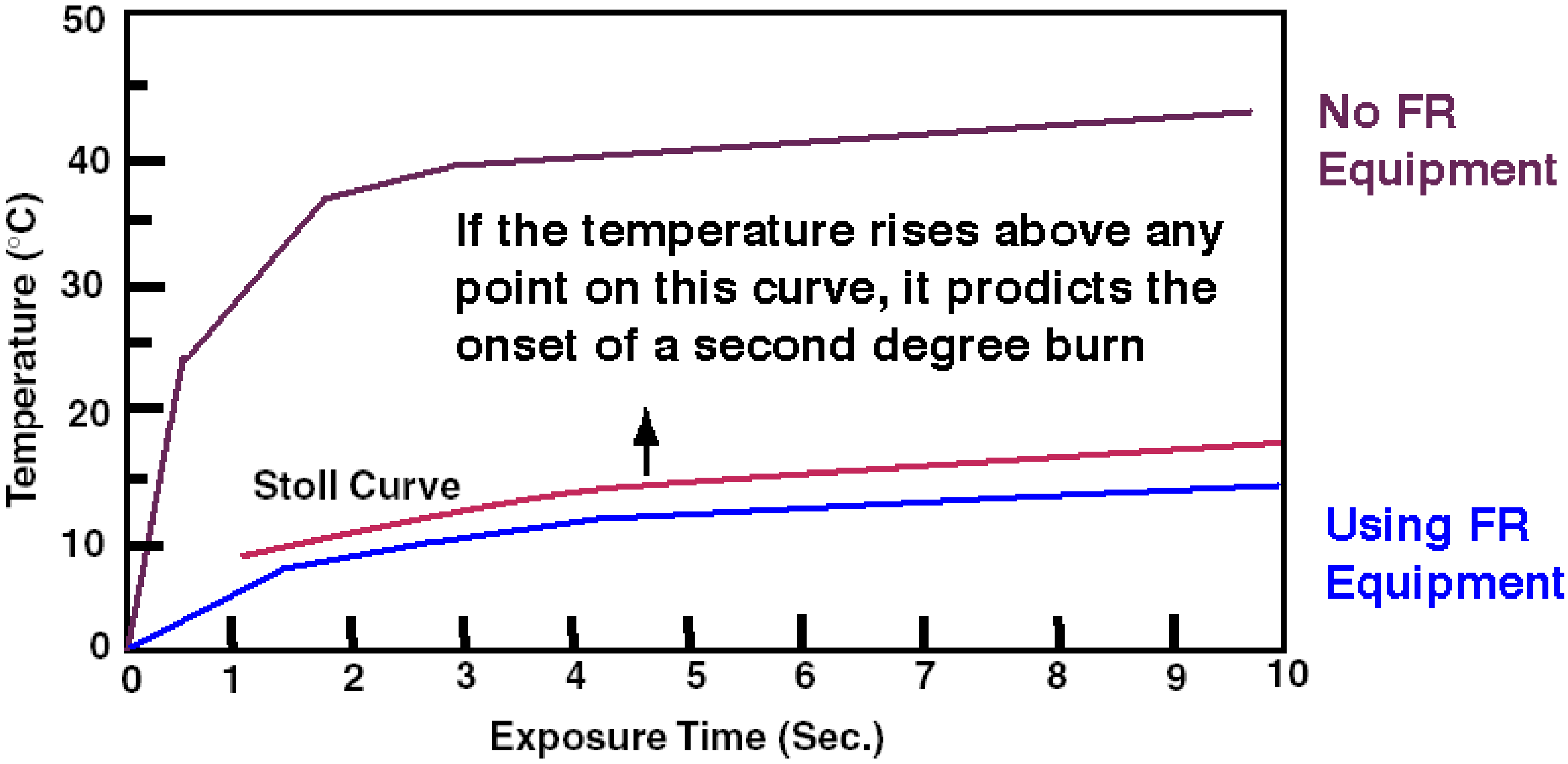
  plus

- Flash Suit

PPE Incident Energy Rating

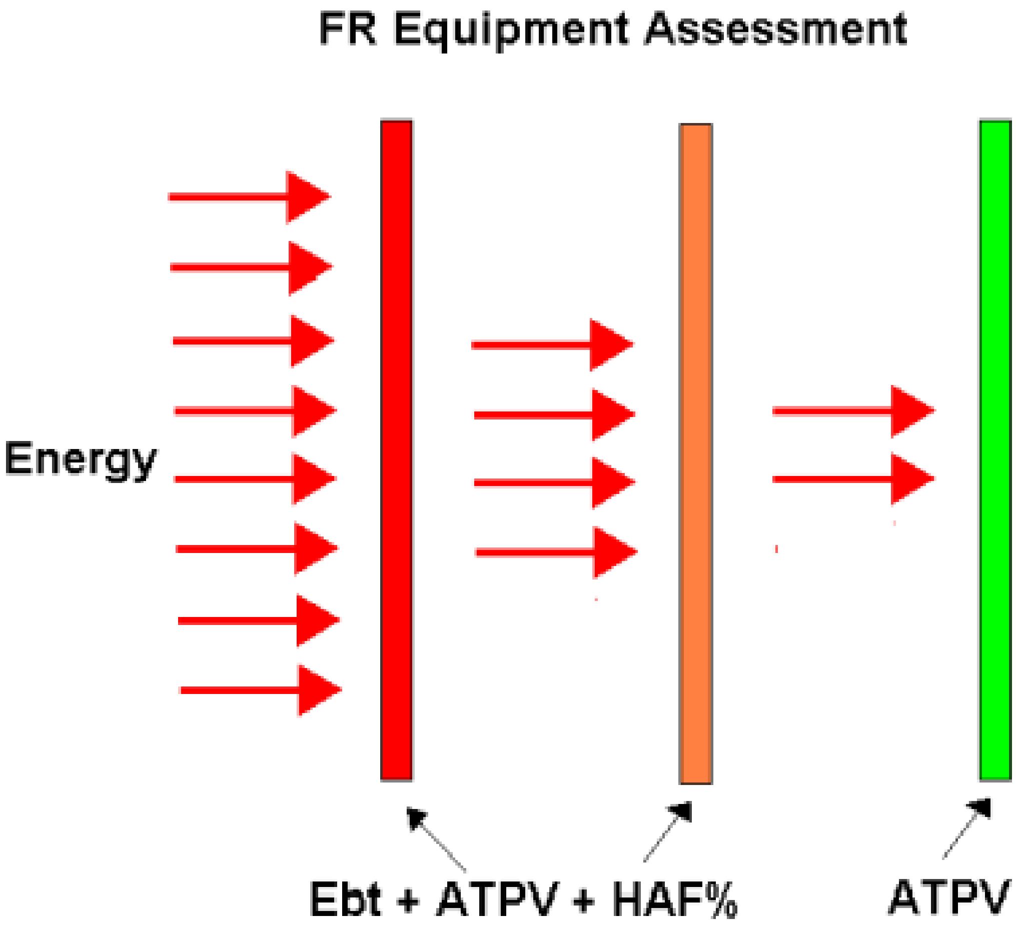
- **ATPV**: is the defined as the incident energy on a fabric or material that results in sufficient heat transfer through the fabric or material to cause the onset of a second degree burn.
- **E_{BT}**: is defined as the average of the five highest incident energy exposures values below the Stoll curve where the specimens do not exhibit breakopen. E_{BT} is reported when the ATPV cannot be determined due to FR fabric breakopen.
- **HAF%:** is the heat transfer capability of the fabric or material

Stoll Curve



If the temperature rises above any point on this curve, it prodicts the onset of a second degree burn

FR Equipment Layering


FR Equipment Assessment
Energy
Ebt + ATPV + HAF%
ATPV

Example of Layered System

$$E' = E_{calculated\,(cal/cm^2)} * \frac{(100 - HAF\%)}{100}$$

- **Proposed PPE for Arc Fault with E = 22 Cal/cm^2**

Proposed Equipment	ATPV Rating (cal/cm^2)	E_{BT} (cal/cm^2)	HAF %
FR Shirt (long Sleeve)	5	9	85
FR Raincoat	10	18	70

Example of Layered System

$$E' = 22 * \frac{(100 - 70)}{100} = 6.6 cal / cm^2$$

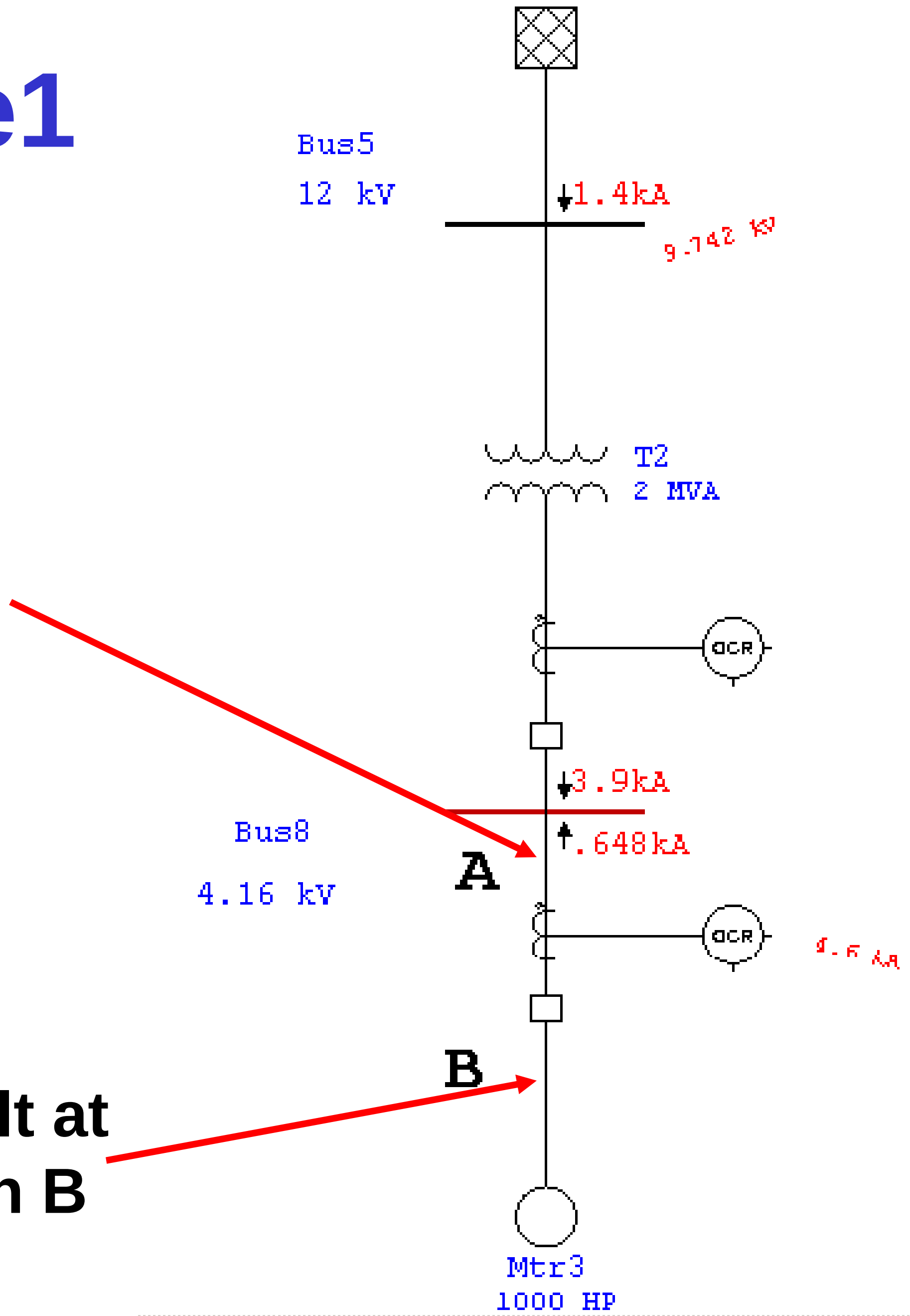
- Energy that passes to second layer is higher than ATPV
- EBT is too low for outer layer (possible breakopen)

Modified Equipment	ATPV Rating (cal/cm^2)	E_{BT} (cal/cm^2)	HAF %
FR Shirt (long Sleeve)	9	9	85
FR Raincoat	15	22	70

Considerations for layering

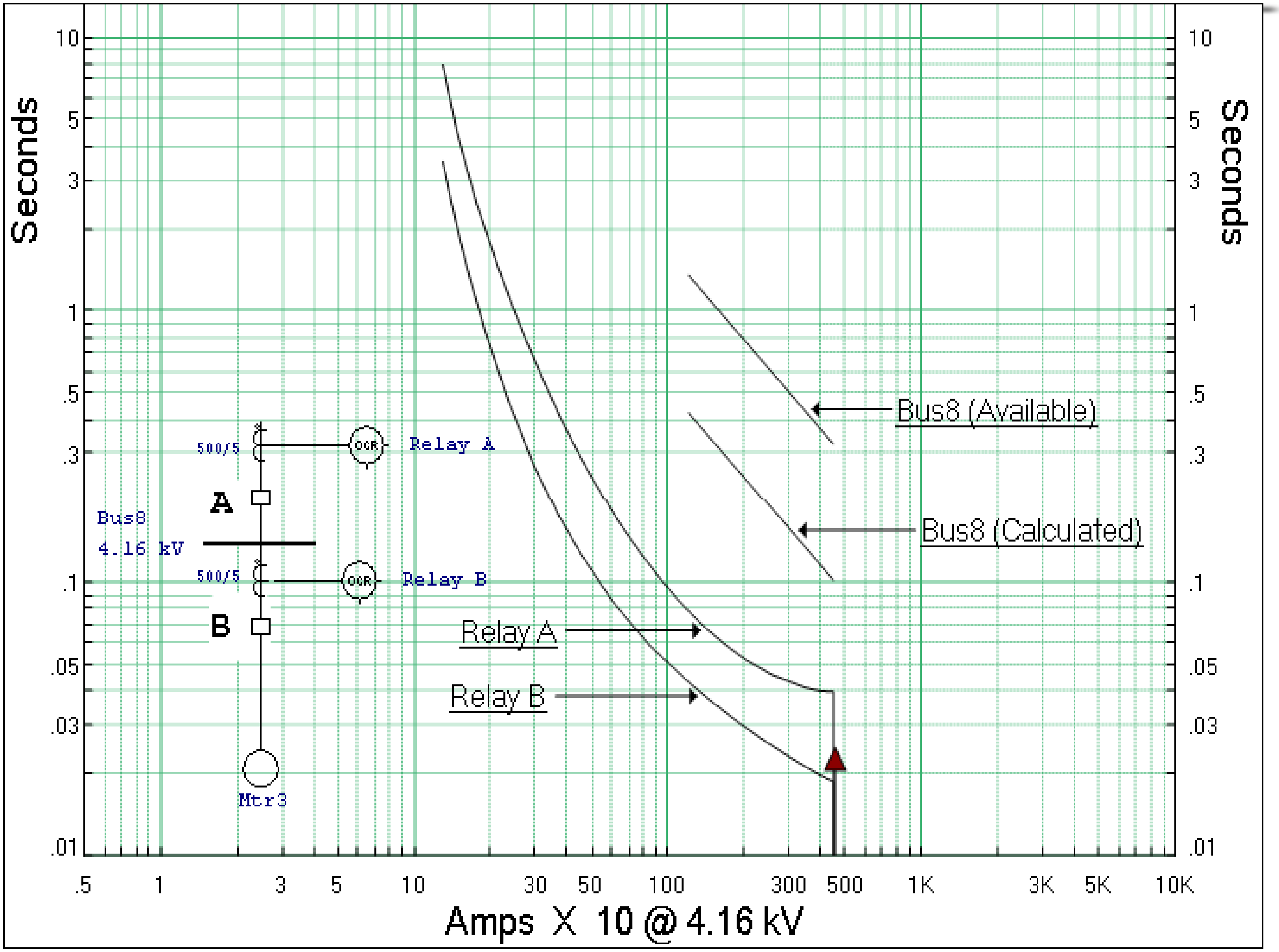
- ATPV rating of the equipment must be above the calculated incident energy of the Arc for single layer FR system
- In multiple layer FR system there must be no breakopen that reaches the innermost layer to prevent possible ignition of such
- NFPA example recommends

Example1


Bus5
12 kV
1.4kA
9.742 kV
T2
2 MVA
OCR
3.9kA
Bus8
4.16 kV
.648kA
A
OCR
4.6 kA
B
Mtr3
1000 HP

Arc Fault at Location A

Arc Fault at Location B



Seconds
10
5
3
1
.5
.3
.1
.05
.03
.01
.5
1
3
5
10
30
50
100
300
500
1K
3K
5K
10K
Amps X 10 @ 4.16 kV
500/5
OCR
Relay A
A
Bus8
4.16 kV
500/5
OCR
Relay B
B
Mtr3
Bus8 (Available)
Bus8 (Calculated)
Relay A
Relay B

Example1

- Fault at location B

  Calculated incident energy = 0.784 Cal/cm^2

  (Relay B operates at 1.206 cycles + 5 cycles HVCB)

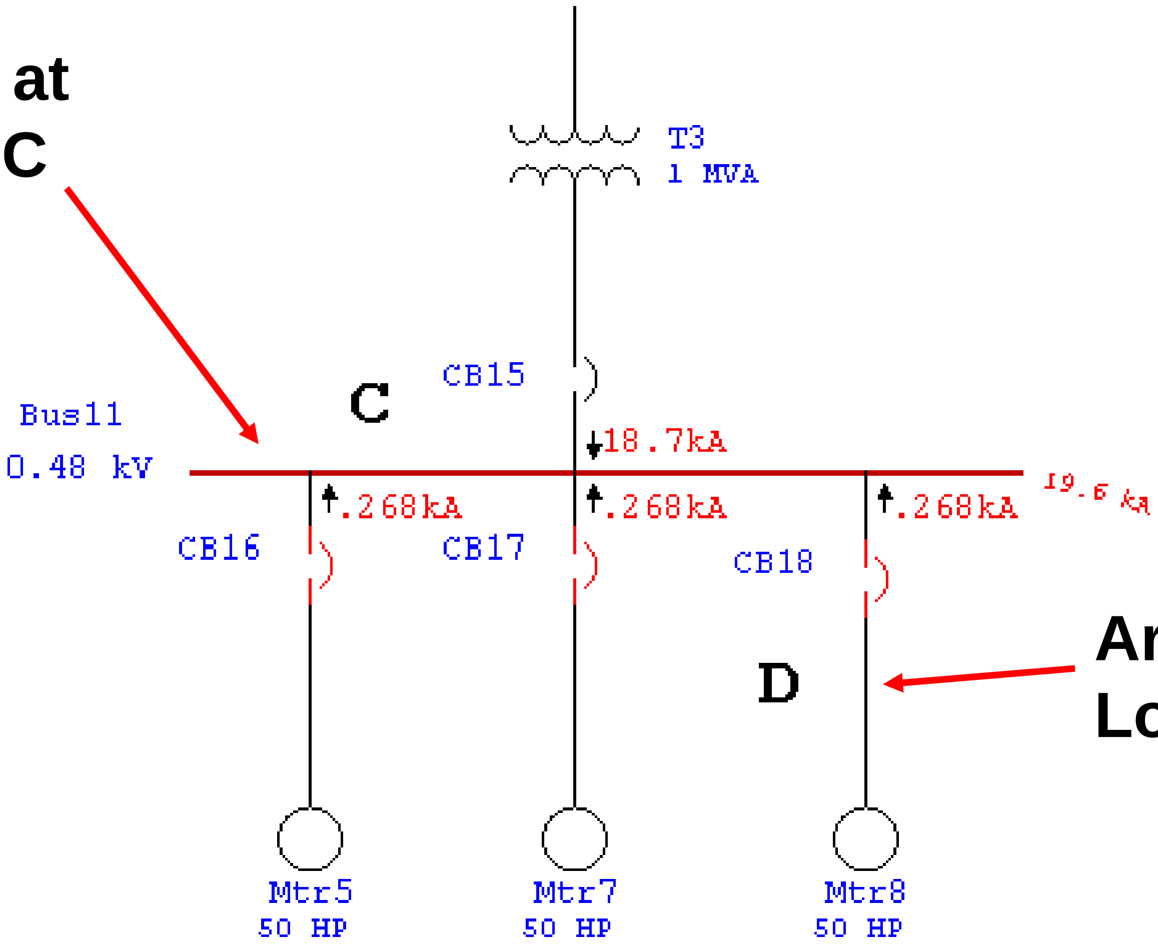
- For a fault at location A

  Calculated incident energy = 0.945 Cal/cm^2

  (Relay A operates at 2.406 cycles + 5 cycles HVCB)

- Hence the Incident Energy to be considered for this system should be 0.945 Cal/cm^2 (the most conservative value).

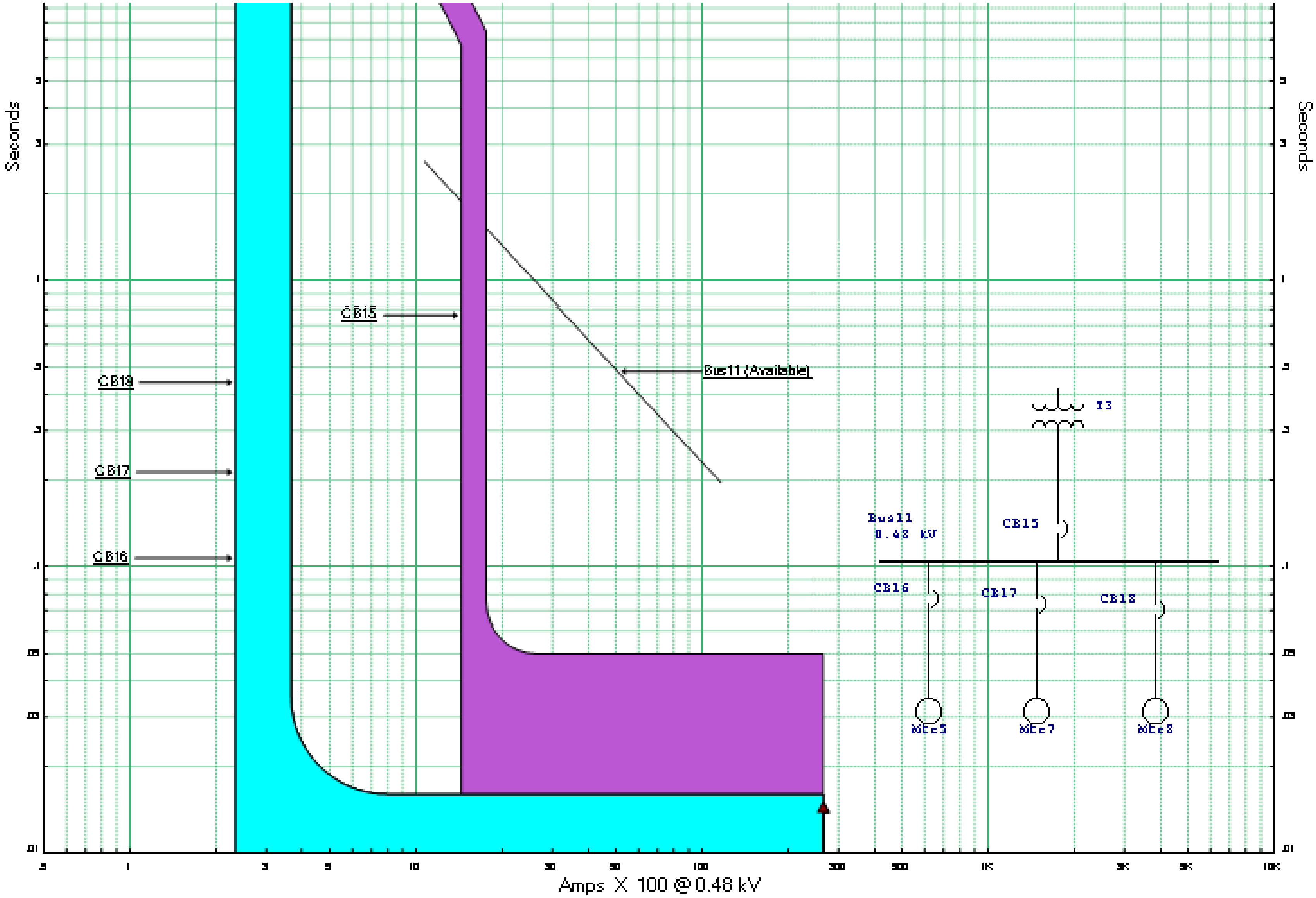
Example 2



T3
1 MVA
CB15
C
Bus11
0.48 kV
18.7kA
.268kA
.268kA
.268kA
19.6 kA
CB16
CB17
CB18
D
Mtr5
50 HP
Mtr7
50 HP
Mtr8
50 HP

Arc Fault at Location C

Arc Fault at Location D



Seconds
CB15
CB18
CB17
CB16
Bus11 (Available)
T3
Bus11
0.48 kV
CB15
CB16
CB17
CB18
MCC5
MCC7
MCC8
Amps X 100 @ 0.48 kV
.5
1
3
5
10
30
50
100
300
500
1K
3K
5K
10K
.01
.03
.05
.1
.3
.5
1
3
5

Example 2

- Fault at location C:

  Calculated incident energy = 7.604 Cal/cm^2

  (LVCB 15 operates in 0.150 sec.)

- For a fault at location D:

  Calculated incident energy = 5.576 Cal/cm^2

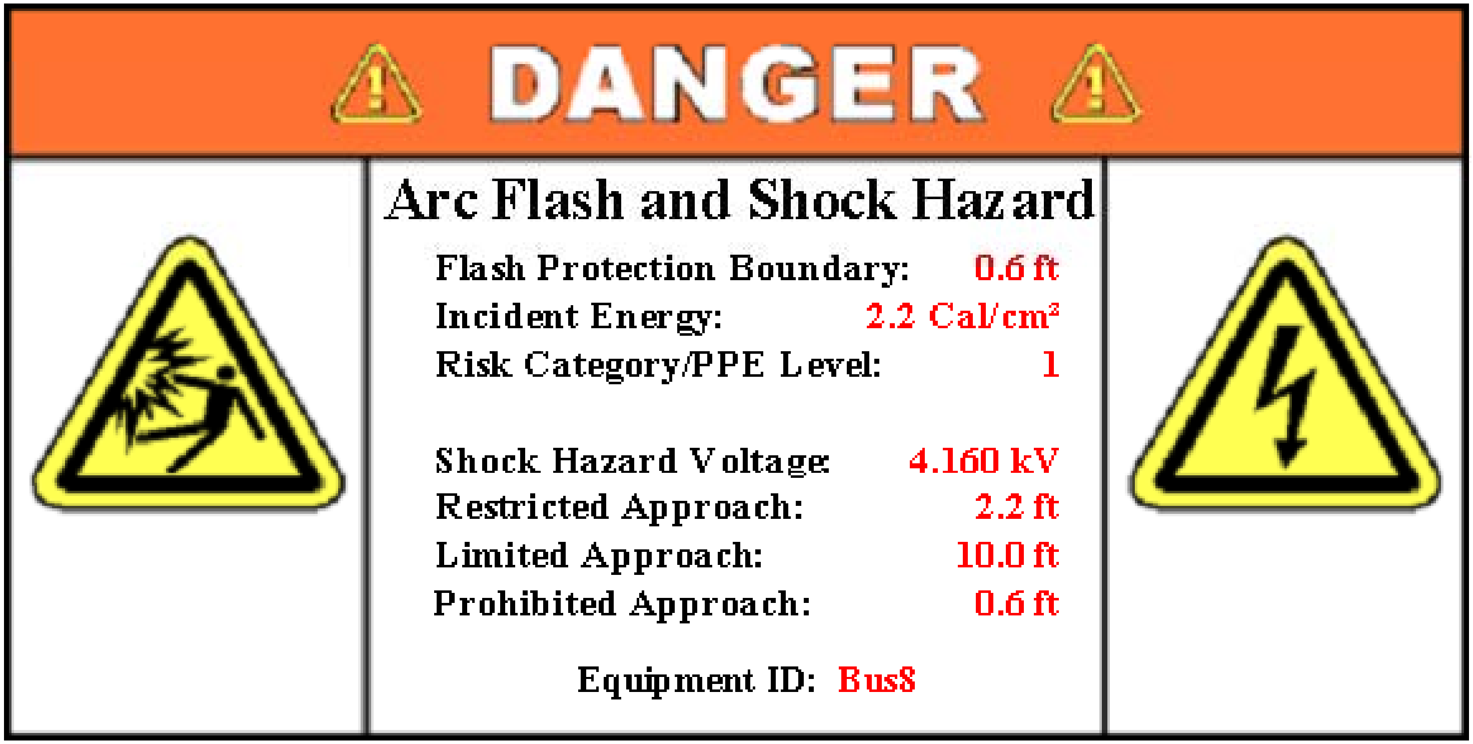
  (LVCB 16, 17 & 18 operate in 0.115 sec.)

- Hence the Incident Energy to be considered for this system should be 7.604 Cal/cm^2 (the most conservative value).

Arc Flash Hazard Labels

- Place labels at each location (cubicle)
- Contain information that is clear and communicates the danger level
- Meet current format per ANSI Z535 2002 (safety symbols)

Examples of Safety Labels

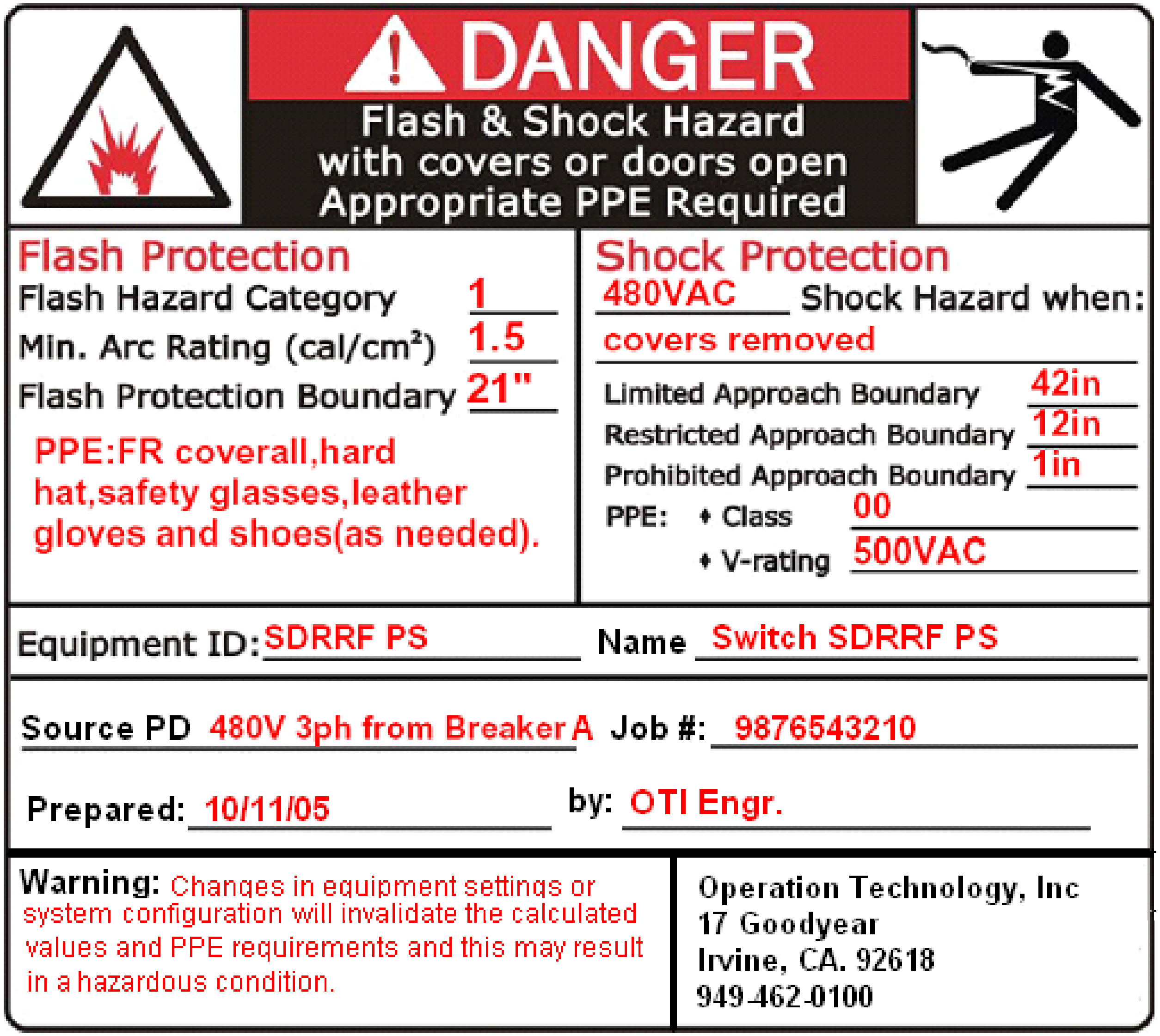


DANGER

Arc Flash and Shock Hazard

Flash Protection Boundary:	0.6 ft
Incident Energy:	2.2 Cal/cm²
Risk Category/PPE Level:	1
Shock Hazard Voltage:	4.160 kV
Restricted Approach:	2.2 ft
Limited Approach:	10.0 ft
Prohibited Approach:	0.6 ft

Equipment ID: Bus8



DANGER

Flash & Shock Hazard
with covers or doors open
Appropriate PPE Required

Flash Protection

Flash Hazard Category 1
Min. Arc Rating (cal/cm^2) 1.5
Flash Protection Boundary 21"

PPE:FR coverall,hard hat,safety glasses,leather gloves and shoes(as needed).

Shock Protection

480VAC Shock Hazard when:
covers removed

Limited Approach Boundary 42in
Restricted Approach Boundary 12in
Prohibited Approach Boundary 1in
PPE: ♦ Class 00
♦ V-rating 500VAC

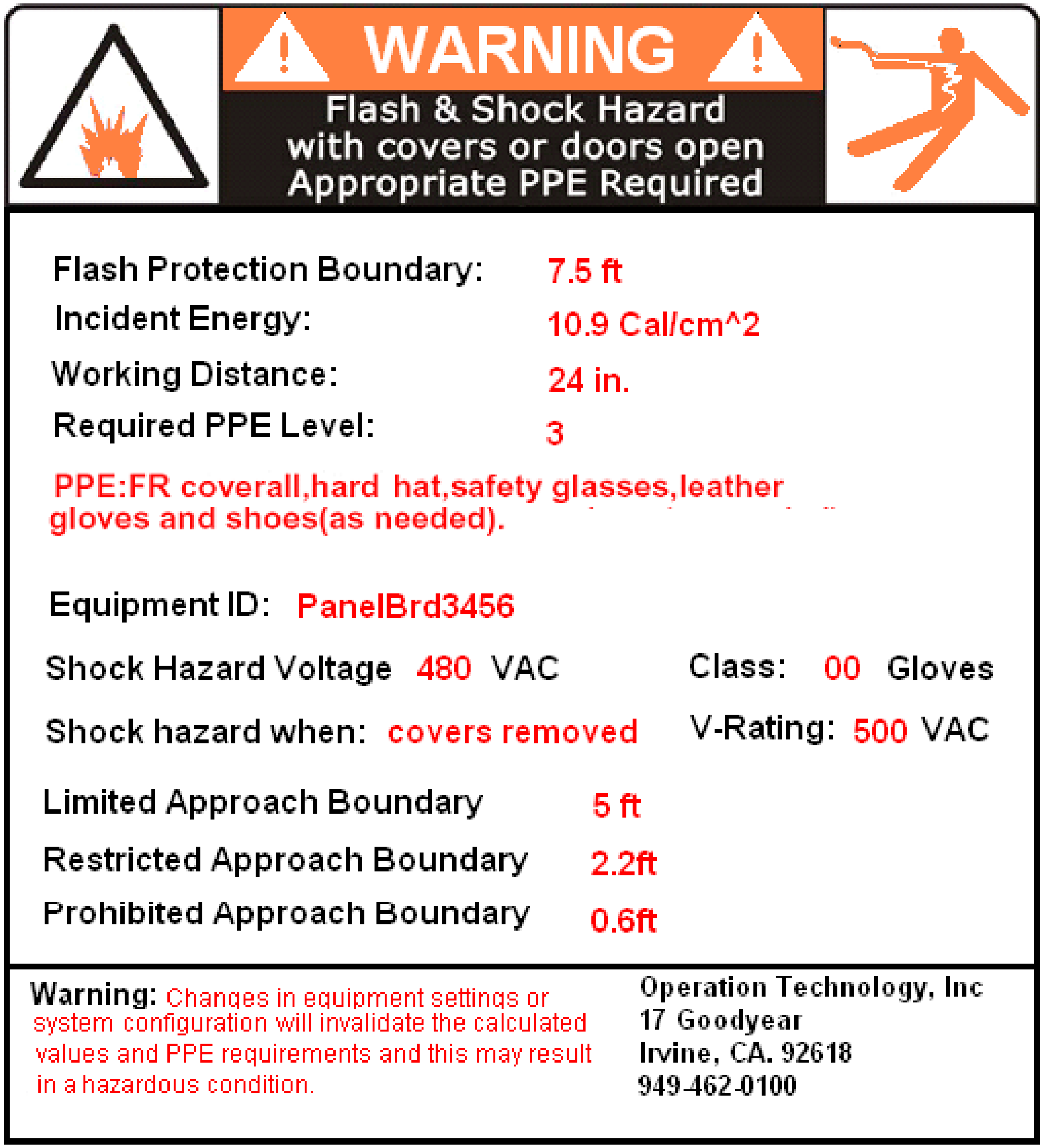
Equipment ID: SDRRF PS
Name Switch SDRRF PS

Source PD 480V 3ph from Breaker A
Job #: 9876543210

Prepared: 10/11/05
by: OTI Engr.

Warning: Changes in equipment settings or system configuration will invalidate the calculated values and PPE requirements and this may result in a hazardous condition.

Operation Technology, Inc
17 Goodyear
Irvine, CA. 92618
949-462-0100



WARNING

Flash & Shock Hazard
with covers or doors open
Appropriate PPE Required

Flash Protection Boundary: 7.5 ft

Incident Energy: 10.9 Cal/cm^2

Working Distance: 24 in.

Required PPE Level: 3

PPE:FR coverall,hard hat,safety glasses,leather gloves and shoes(as needed).

Equipment ID: PanelBrd3456

Shock Hazard Voltage 480 VAC

Class: 00 Gloves

Shock hazard when: covers removed

V-Rating: 500 VAC

Limited Approach Boundary 5 ft

Restricted Approach Boundary 2.2ft

Prohibited Approach Boundary 0.6ft

Warning: Changes in equipment settings or system configuration will invalidate the calculated values and PPE requirements and this may result in a hazardous condition.

Operation Technology, Inc
17 Goodyear
Irvine, CA. 92618
949-462-0100

ASTM Insulating Glove Voltage Classes

Types of Insulating Glove	Max. use voltage AC (L-L) (V-Rating field)	Class	Bus nominal kV range
Low Voltage Gloves	500	00	kV ≤ 0.500 Bus kV ≤≥
	1000	0	0.500 kV < Bus kV ≤ 1.0 kV
High Voltage Gloves	7500	1	1.0 kV < Bus kV ≤ 7.5 kV
	17000	2	7.5 kV < Bus kV ≤ 17.0 kV
	26500	3	17.0 kV < Bus kV ≤ 26.5 kV
	36000	4	26.5 kV < Bus kV ≤ 36.0 kV

Solutions to Arc-Flash Problems

- **Infrared Analysis:** which allow inspections of the equipment to be made without exposure to the equipment (inspections of load, connection, component fatigue and overheating without opening the equipment).
- **Remote Racking Systems:** which allow the racking of circuit breakers at a safe distance and thus reducing the amount of incident energy exposure.

Solutions to Arc-Flash Problems

- **Low Arc Flash Circuit Breakers :** which are designed to blow open the terminals in an amount of time comparable to current limiting fuses.
- **Arc-Flash Detecting Circuit Breakers:** devices which can sense a combination of arcing current and the light emitted by an arc (cause the main circuit breaker to open to extinguish the fault).

Solutions to Arc-Flash Problems

- **Current Limiting Fuses:** Fuses designed to operate very fast at certain current levels. Will work for a lot of situations, but they may introduce coordination problems and nuisance tripping.
- **De-energize When Possible :** The best strategy to protect against arc-flash dangers is to de-energize the equipment if possible at all.

Solutions to Arc-Flash Problems

- **Replacing Switchgear with Arc Resistant Switchgear**
- **Adding a Secondary Relay that can trip the Primary Breaker**
- **De-energize When Possible :** The best strategy to protect against arc-flash dangers is to de-energize the equipment if possible at all.